NA60+: an overview of the experiment at the CERN SPS

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on behalf of the NA60+ collaboration

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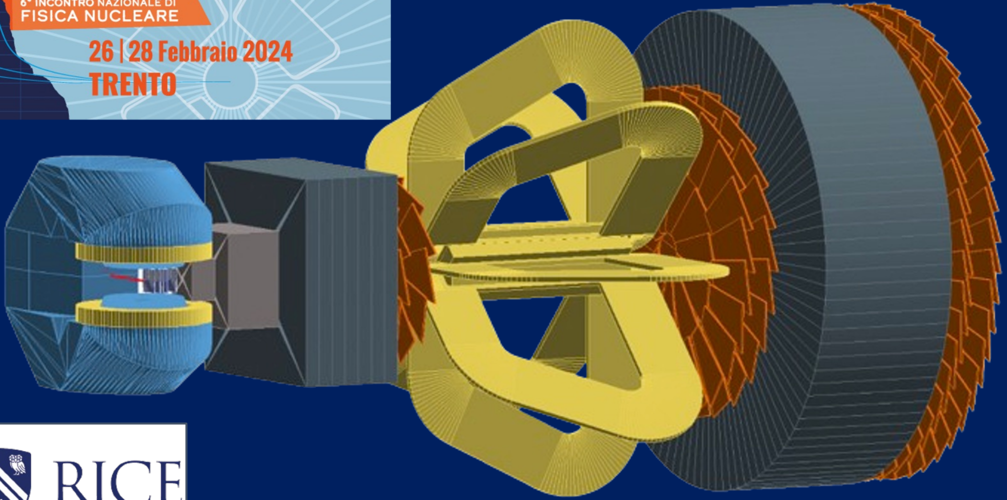
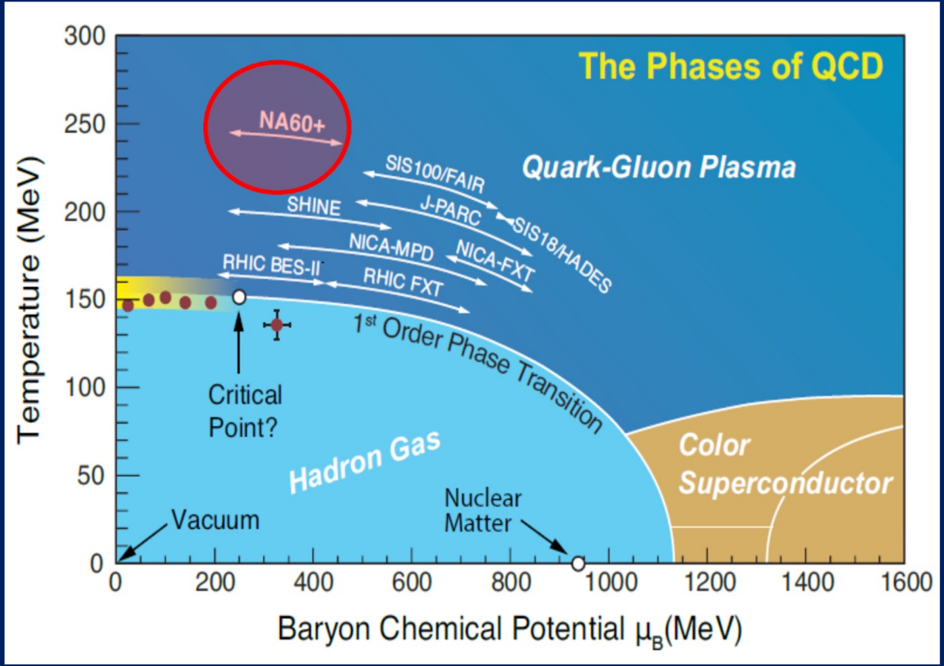


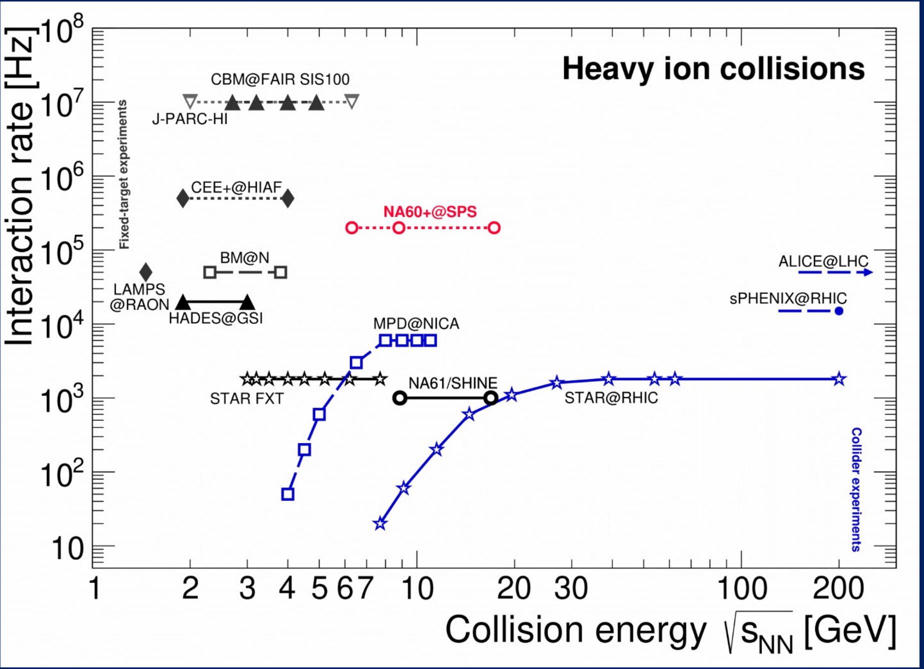
NA60+

- New experiment at CERN SPS
  - heavy-ion collisions at **low centre-of-mass energies ($\sqrt{s_{NN}}$ ~ 5 to 17 GeV)** → unique tool to investigate the **QCD phase diagram** at large values of the **baryochemical potential (200<μ_B<500 MeV)**
- Open points at high μ_B :
  - The **first-order of the phase transition** at large μ_B
  - The presence of a **critical point**
  - **Chiral symmetry restoration effects**
  - Properties of QGP at high μ_B
  - The temperature at which the **onset of deconfinement** occurs



NA60+

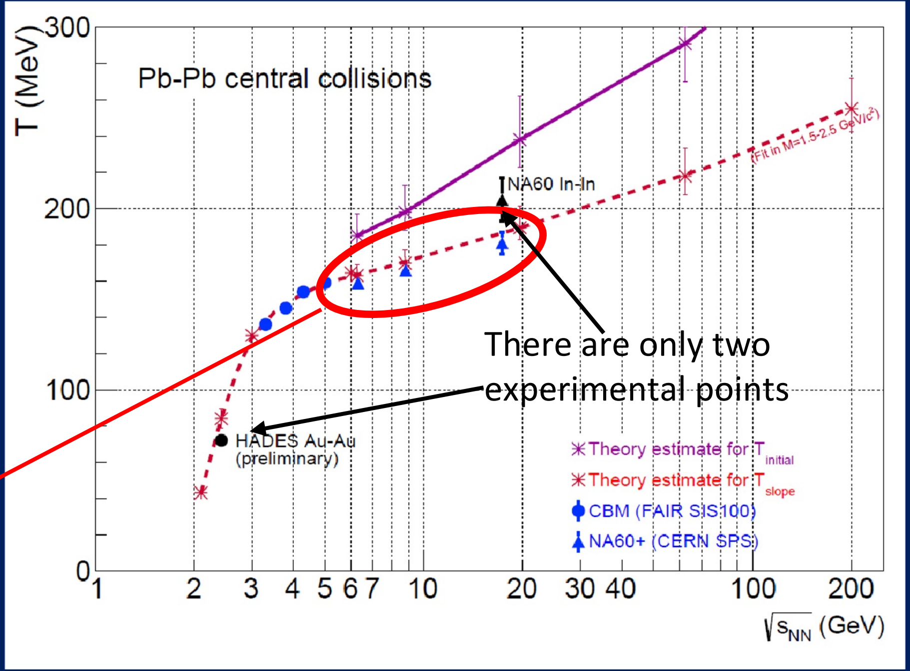
- **Beam energy scan** in the range $\sqrt{(s_{NN})}$ **~ 5 to 17 GeV and high interaction rate > 10^5 Hz**
  - allows the study of the QCD phase diagram in the range of μ_B **200–500 MeV**
- NA60+ stands out for its **exclusive coverage of the energy range and interaction rate**
- LHC scan higher temperatures and $\mu_B \sim 0$
- NA61/SHINE and RHIC scan the same energy range
  - lower interaction rate (factor 100) and results mostly on soft processes



Physics motivations: em probes

- **Electromagnetic probes (dileptons)** providing insights into:
  - The **temperature** of the system via the measurement of the **thermal dimuon mass spectrum**
  - **Chiral symmetry restoration effects ρ-a_1 chiral mixing**
  - The **order of the phase transition**
  - **Dimuon elliptic flow**: first measurement at SPS energies

$\sqrt{s_{NN}}$ range covered by NA60+ ➞ complementarity with **CBM**



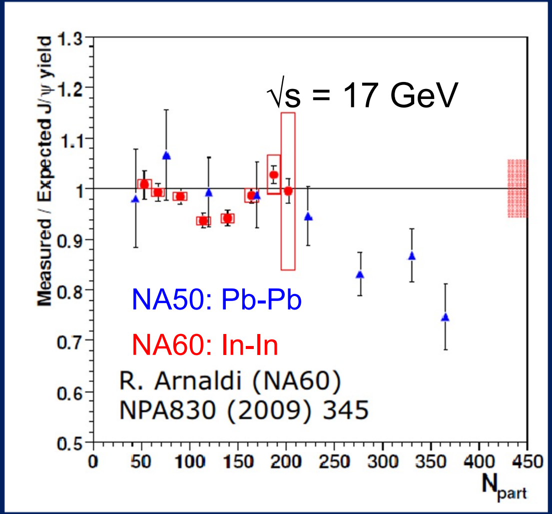
Compilation T. Galatyuk, QM2018
Hades,Nature Phys, 15(2019) 1040
√s>6 GeV, R. Rapp, PLB 753 (2026) 586
√s<6 GeV, T. Galatyuk, EPJA 52 (2026) 131

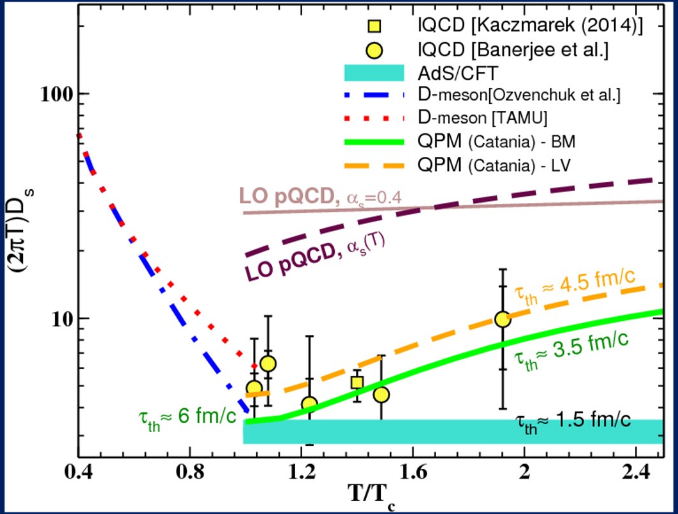
Physics motivations: hard probes

- **Charmonium suppression**: signal of the **deconfinement**
  - NA60+ can explore the centrality dependence of **J/ψ suppression vs √s**
- **Open charm states**: **transport properties** of the Quark-Gluon Plasma at large μ_B
  - Measure 2 and 3 prong decays of charmed mesons and baryons:
    - R_{AA},v_2 : **transport coefficients**
    - Λ_c ,D, D_s : study **hadronization mechanisms**

★ J/ψ suppression observed at top SPS energies

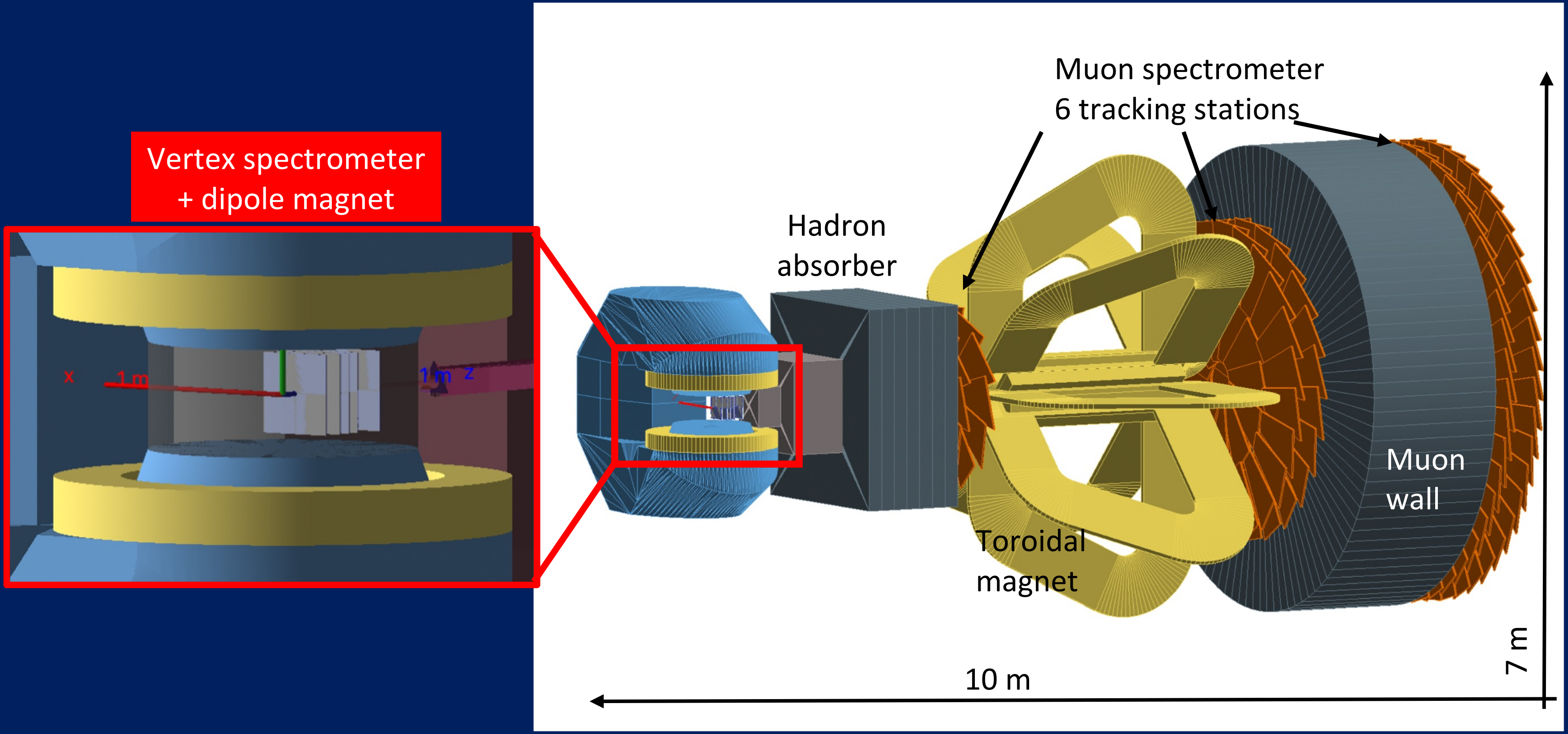
★ No open charm measurements at SPS energies





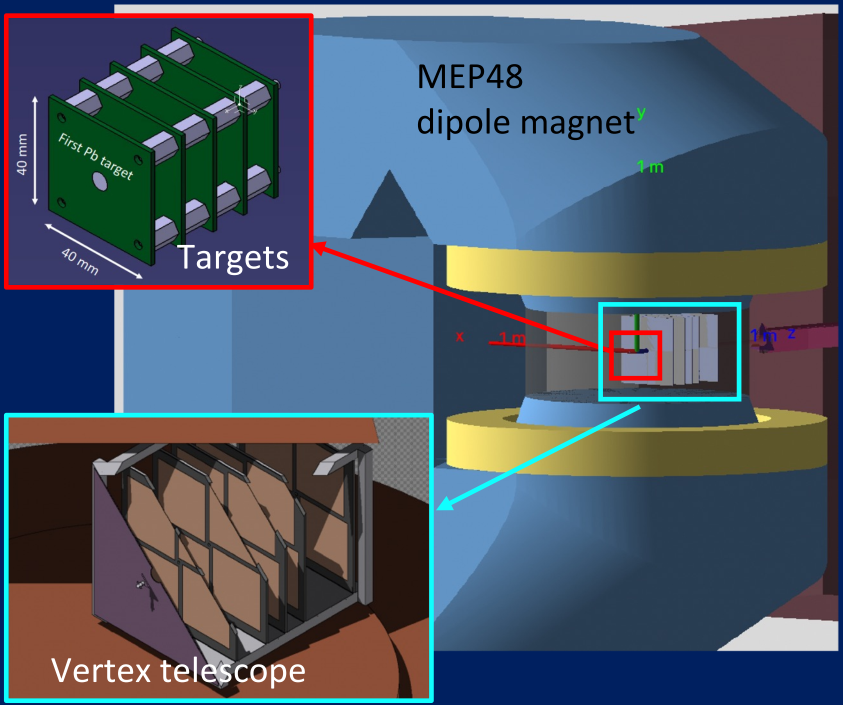
Also study strangeness and hypernuclei production via their hadronic decays

NA60+ experimental setup



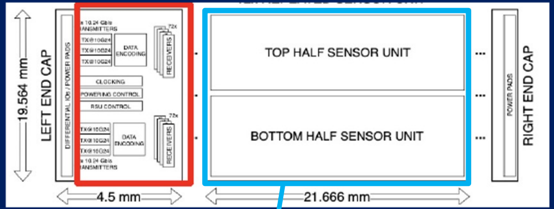
Vertex region

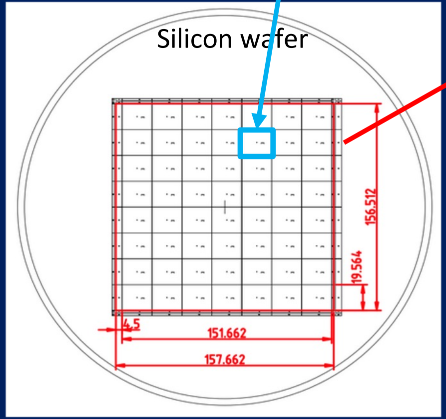
- MEP48 magnet → 1.5 T available at CERN
- Target system for Pb-Pb configuration: five 1.5 mm thick Pb disks spaced by 12 mm
- Vertex spectrometer: 5 layers of large area pixel sensors placed at $7 < z < 38$ cm starting from the closest target
- Vertex spectrometer requirements for high charged particle multiplicity in Pb-Pb collisions:
    - Fast readout
    - Low material budget
    - High granularity and spatial resolution
    - Low power consumption

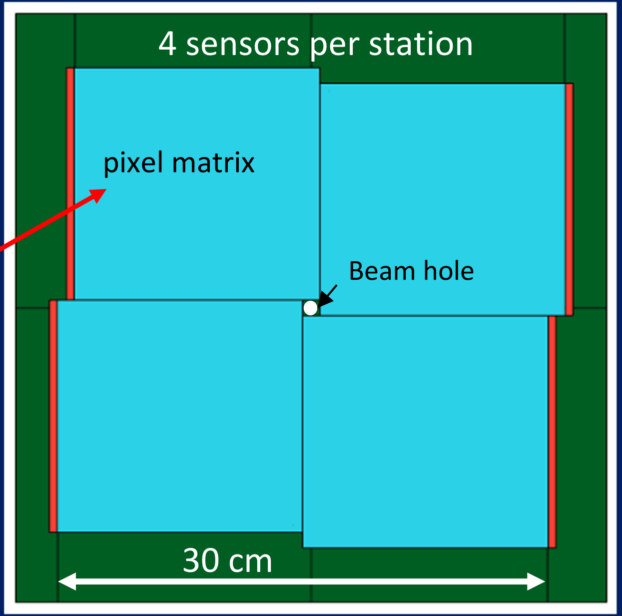


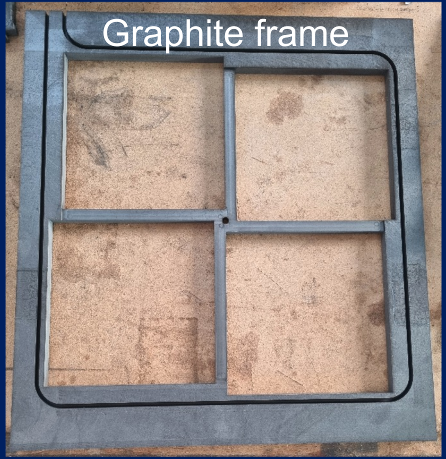
Vertex spectrometer

- Each telescope plane contains 4 large area silicon pixel sensors → state of the art **monolithic active pixel sensors (MAPS)**
- Synergy with ALICE ITS3: first prototypes of large area MAPS (MOSS) ongoing tests
  - Sensor based on ~25 mm long units, replicated several times through **stitching** up to **15 cm length** for NA60+







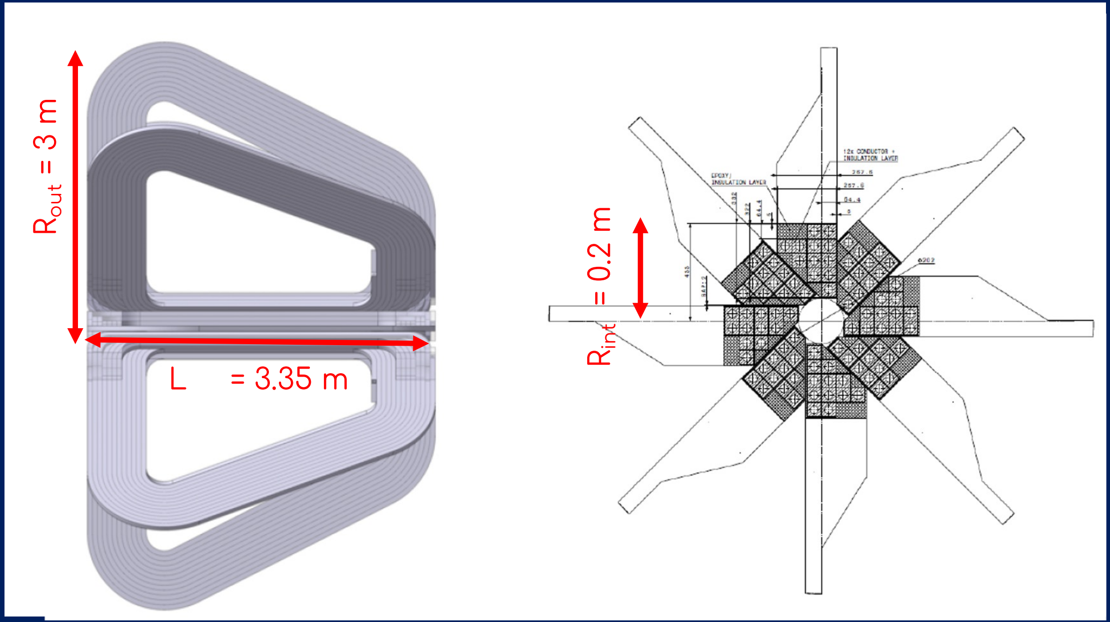


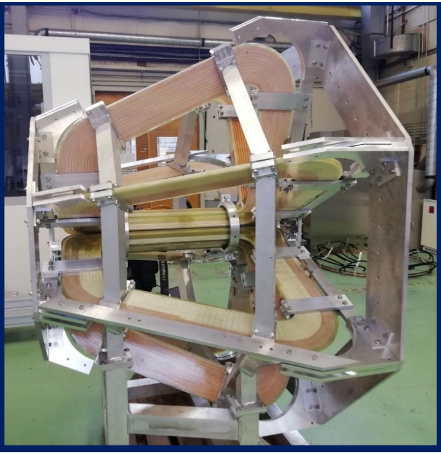
- 0.1% X_0 material budget
- < 5 μm spatial resolution
- <70 mW/cm^2 power consumption

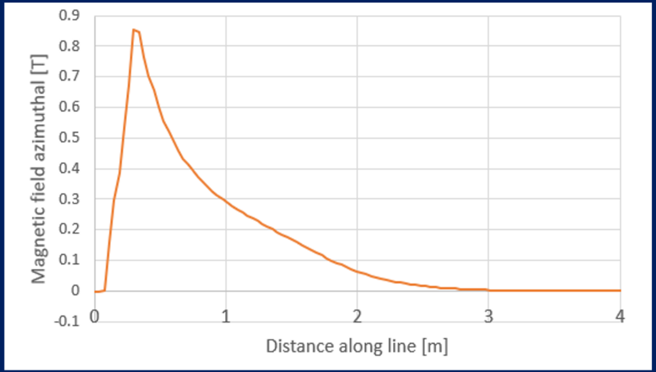
Toroidal Magnet

EP-DT
Detector Technologies

- Eight sectors with 12 turns per coil
- Light design ➞ **low material budget** in the acceptance area
- **Prototype (1:5 scale)** built and tested in 2020-2021 to check calculations and investigate mechanical solutions ➞ **works as expected**

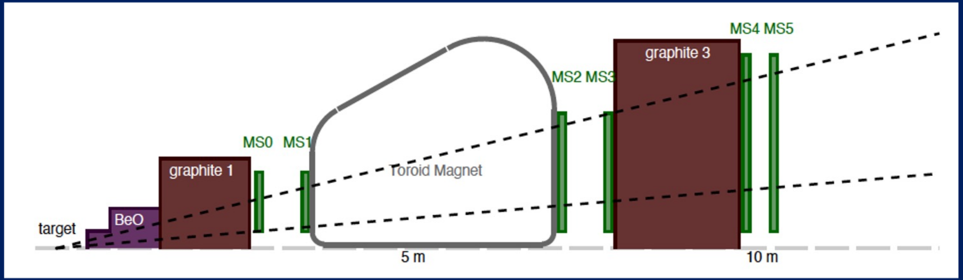


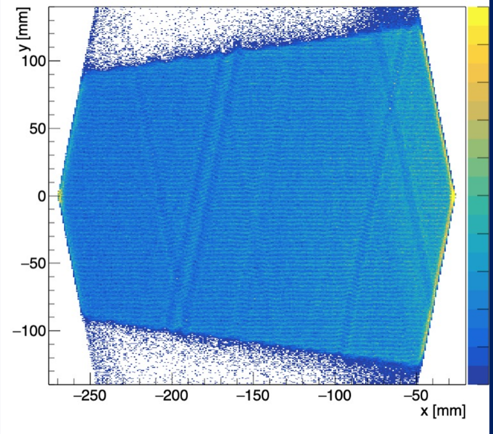


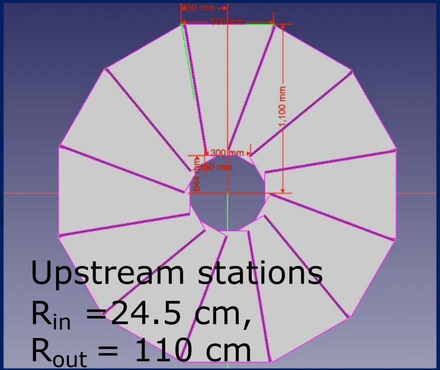


Muon chambers

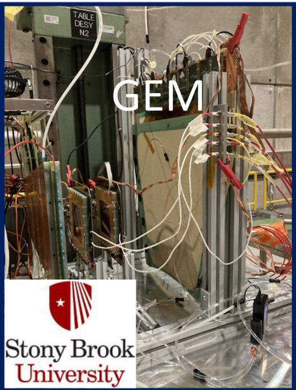
- Thick hadron absorber (235 cm of BeO + graphite)
- With a 10^6 ions/s beam ➞ charged particle rate ~2kHz/cm^2
- The rate can be matched by **MWPC** or **GEM**

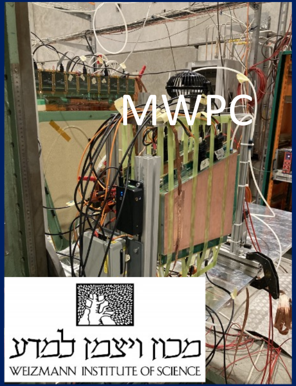






Upstream stations
R_{in} =24.5 cm,
R_{out} = 110 cm

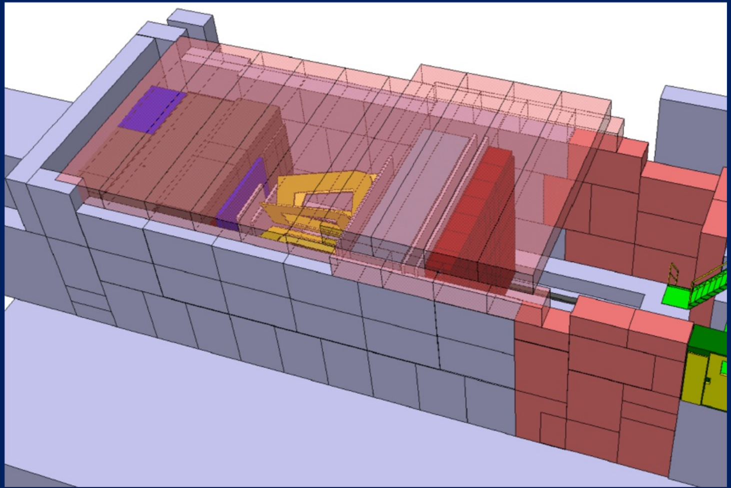


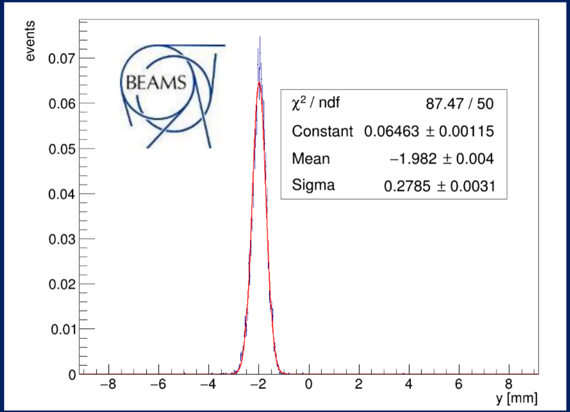


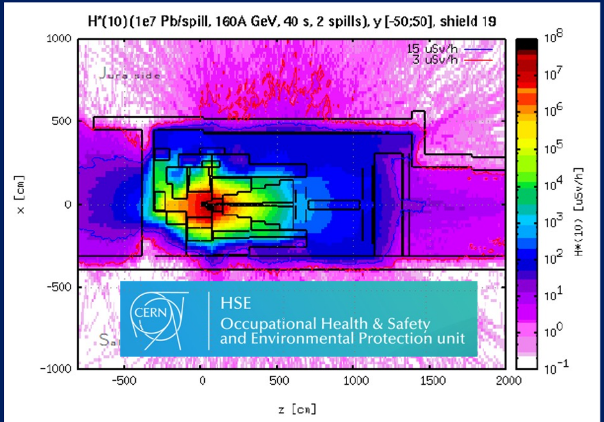
- **MWPC** built and tested at Weizmann institute and during testbeam at CERN SPS in october 2023
  - Spatial resolutions: σ_y~0.5 mm - σ_x~0.1 mm

Beam and radioprotection studies

- NA60+ will be installed in the CERN EHN1 - PPE138 area along the H8 beam line
- **High-intensity** (10^6 ions/s)
- **Heavy shielding** of iron and concrete:
  - Dose below 3 μSv/h externally to the experiment
- Integration studies for detector and infrastructure were also performed
- **Collimated** beam ➞ a fully re-designed optics
  - Testbeam campaign started in 2022 (E=150 GeV): november 2022 - october 2023: promising results (σ ~ 280 μm)

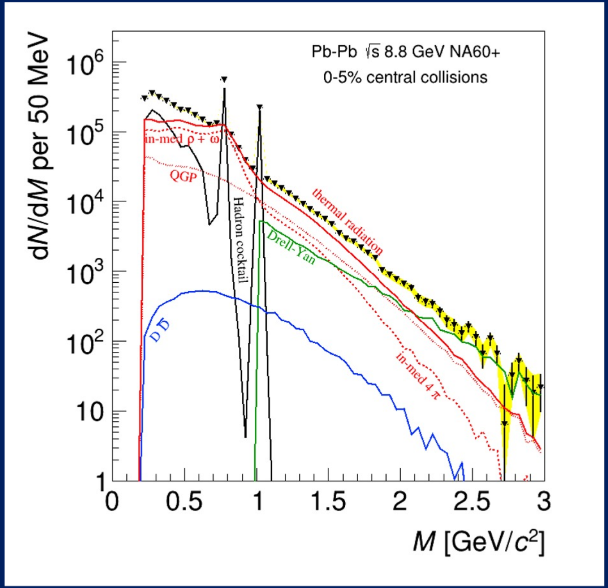


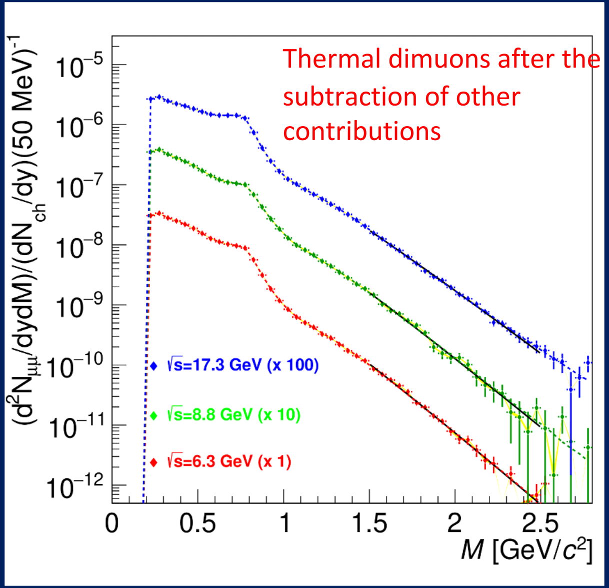




Thermal dimuons mass spectra

- $2x10^7$ reconstructed pairs for each energy ∼ 1 month data taking
  - minimum bias collisions ∼ 20 times the NA60 with similar background and better mass resolution
- Thermal radiation yield measurable up to 2.5 - 3 GeV
- **Extract temperature via fit** of the thermal dimuon spectrum in 1.5 < M < 2.5 GeV

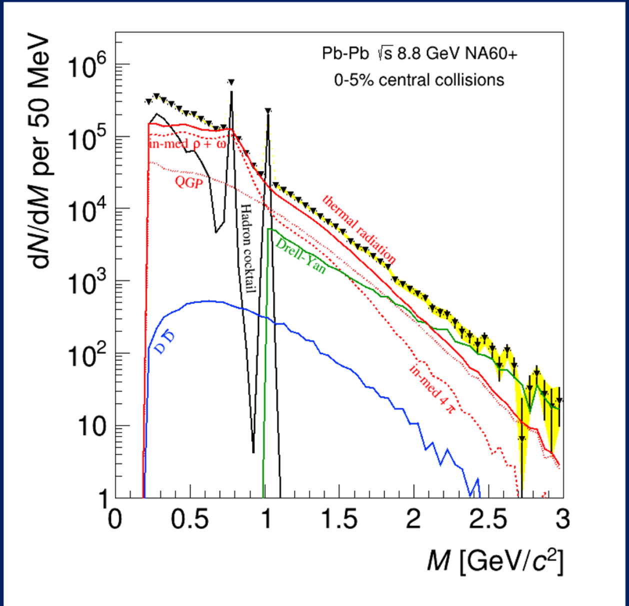


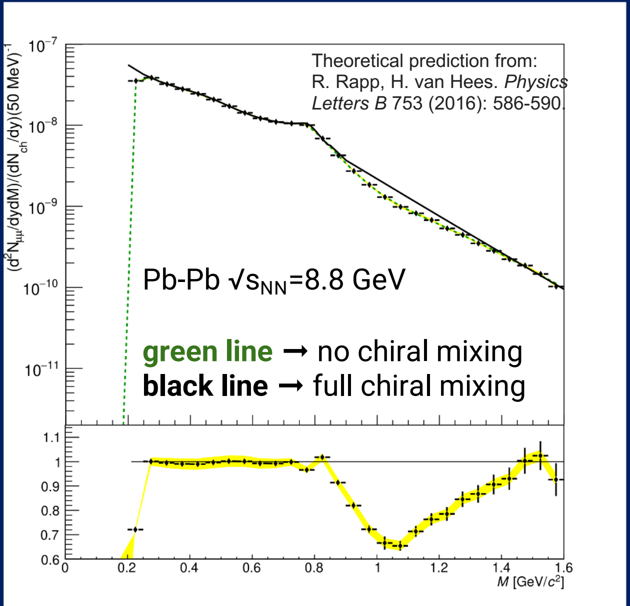


- ∼2% uncertainty on the T_s measurement
- Allows an accurate mapping of the √s-dependence of T_s around T_c

Chiral restoration via ρ-a_1 mixing

- 20-30% enhancement is expected in the region 0.8 < M < 1.5 GeV w.r.t. no mixing
- Good sensitivity to the increase of the yield due to the chiral mixing

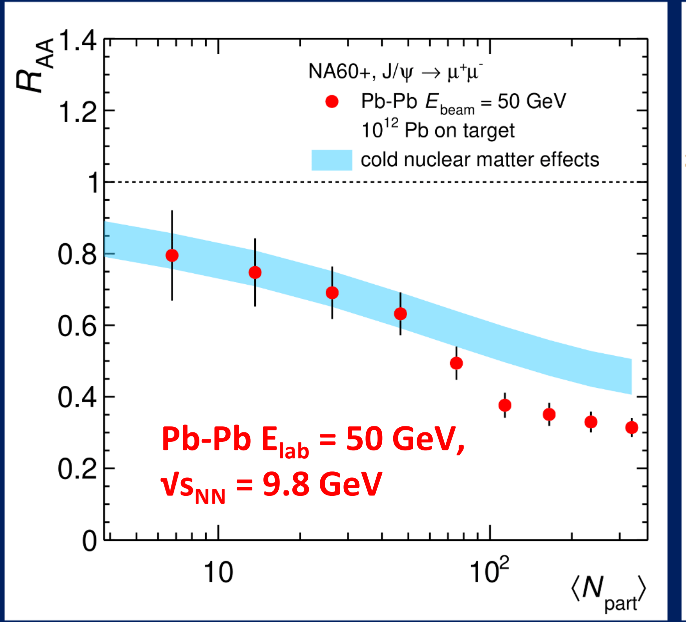


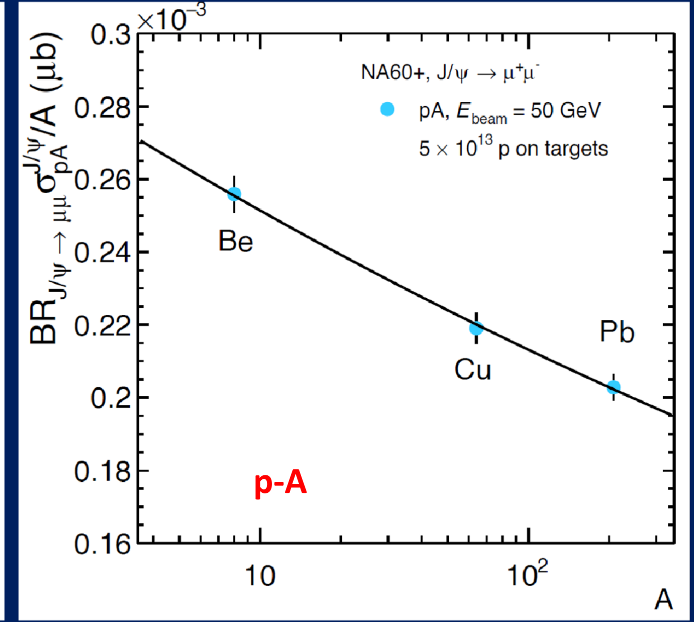


- NA60+ could clearly detect a signal of chiral symmetry restoration

J/ψ suppression

- Low cross section at low energy: 3×10^4 J/ψ in 30-days data taking
- p-A mandatory to calibrate break-up of J/ψ in cold nuclear matter (needed 3-4 nuclear targets and 3×10^8 p/s for 15 days)



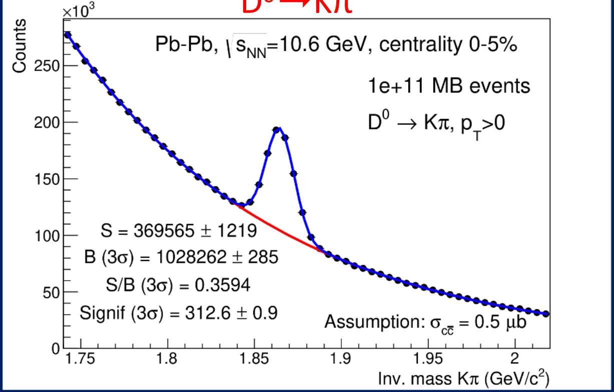


- ~O(10^4) J/ψ at √s = 9.8 GeV
- ~O(10^5) J/ψ at √s = 17.3 GeV
- Allows detection of onset of anomalous suppression effects down to low SPS energy

Open charm

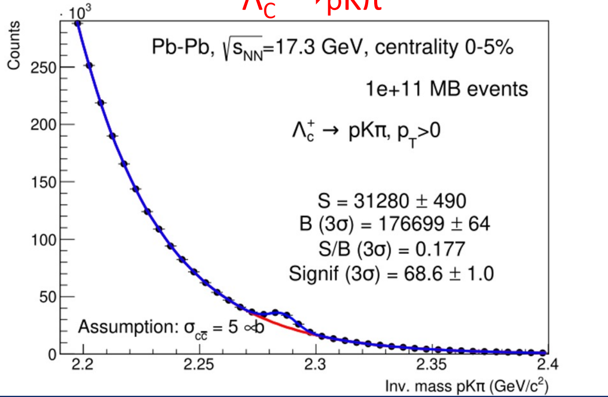
- Decay products reconstructed in the vertex spectrometer
- Geometrical selections on the displaced decay-vertex topology (cτ∼60-300 µm) to enhance the S/B
- All simulations based on 10^{11} minimum bias events in Pb-Pb collisions (∼1 month data taking)

$D^0 \rightarrow K\pi$

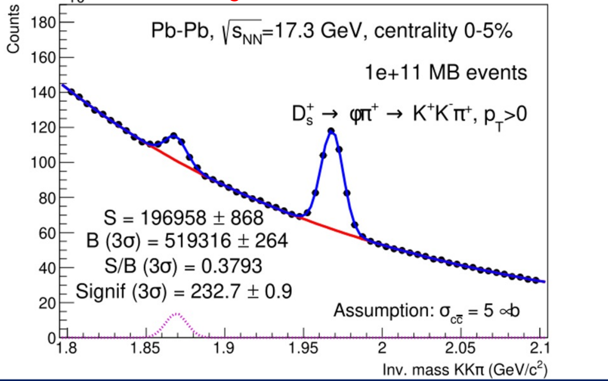


- Allows for **differential studies** of yield and v_2 vs p_T, y and centrality
- NA60+ will be **able to measure D^0, D^+, D_s^+, Λ_c^+, and possibly $\Xi_c^{0,+}$**

$\Lambda_c^+ \rightarrow pK\pi$

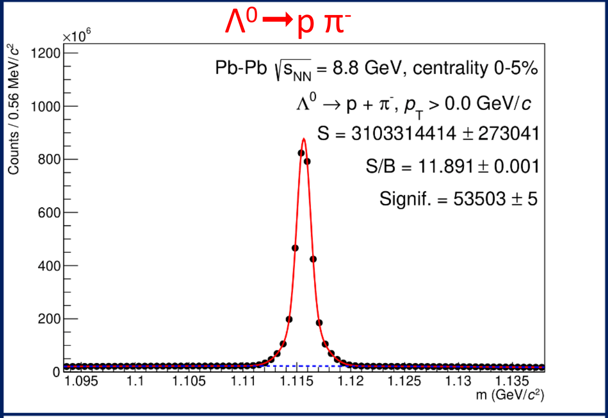


$D^+_S \rightarrow \phi\pi \rightarrow KK\pi$

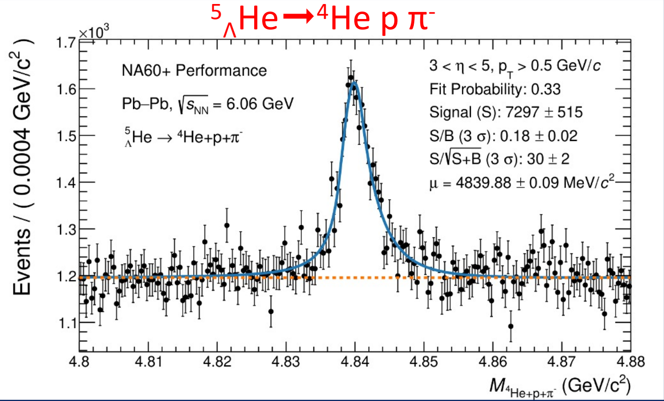


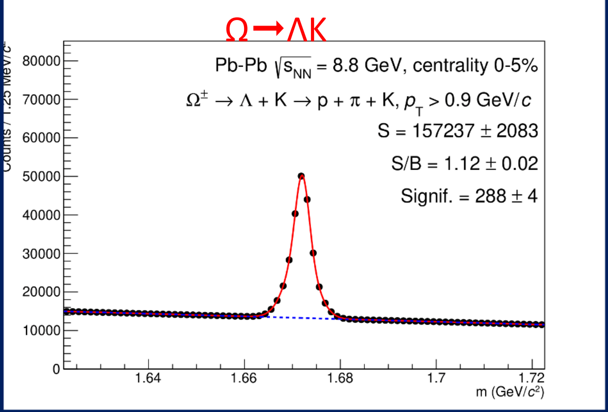
Strangeness and hypernuclei

- Strange baryons and hypernuclei are abundantly produced at SPS energies
- Performance studies for K^0_S, Λ^0, ϕ, Ξ and Ω hyperons:
  - **Strong improvement in their measurement w.r.t. the NA49 and NA57 measurements ➞ possibility of v_2 measurements**



- Decay products reconstructed in the vertex spectrometer as for the open charm





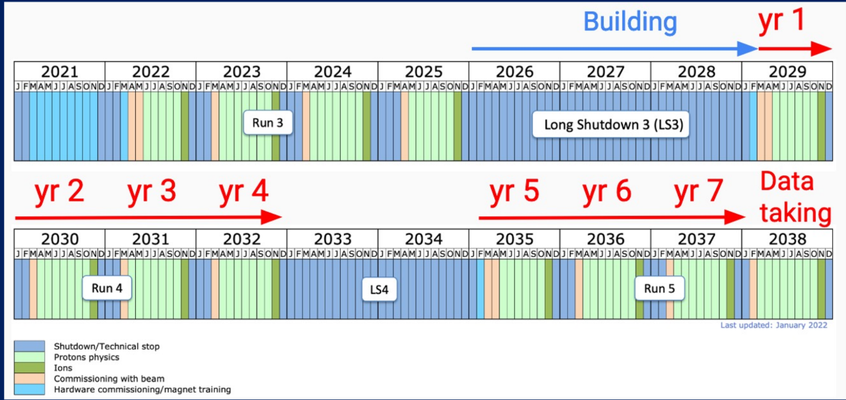
- **High precision** of for the measurement of the properties of Λ hypernuclei
- **Possible discovery** of light Ξ and **Σ hypernuclei**

Timeline

- NA60+ is part of the **CERN Physics Beyond Colliders** initiative since 2016 ➞ substantial support on several technical aspects
- The **Letter of Intent** (http://cds.cern.ch/record/2845376) was submitted in 2022 ➞ discussed with CERN SPSC in February 2023 with favorable feedback:

> The SPSC **recognizes the fundamental interest of the measurements proposed by the NA60+ collaboration**, which are focused on electromagnetic and hard probes of the quark gluon plasma at high baryochemical potential. In order for the project to proceed with the suggested roadmap (starting construction in 2026 and data taking in 2029), **the SPSC would expect to start examining a proposal by 2024**

- The technical proposal should be submitted ~ end 2024
- Start construction in 2026 to start taking data after the Long Shutdown 3 in 2029



- Foresee **at least 7 yrs** of data taking (one energy point per year with p-A and Pb-Pb)

Conclusions

I hope I have provided a clear and engaging overview of the intriguing new experiment, NA60+.

We welcome additional teams to join the effort! There is still room for impactful contributions in various areas: gas detectors, MAPS, magnet, trigger systems, and data acquisition (DAQ)

https://na60plus.ca.infn.it/

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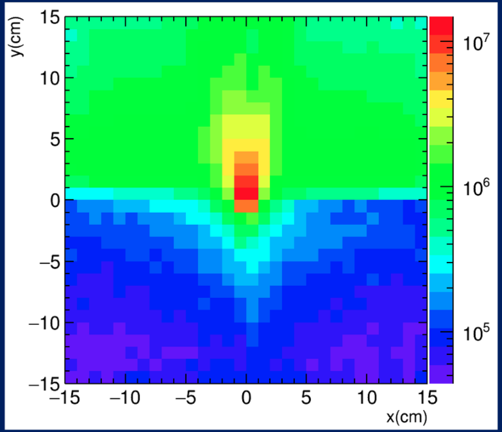
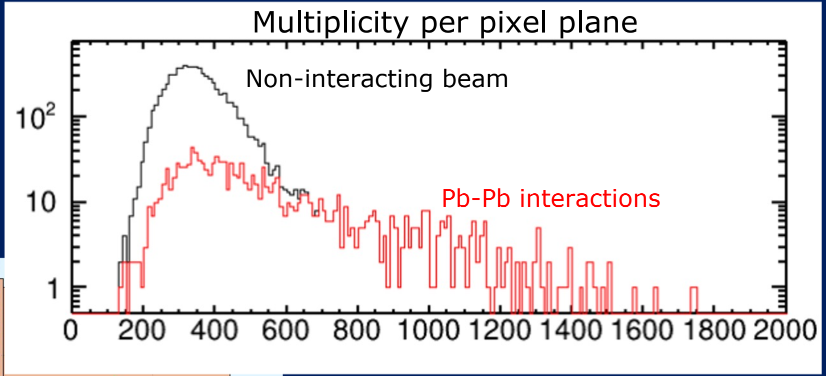
Backup slides

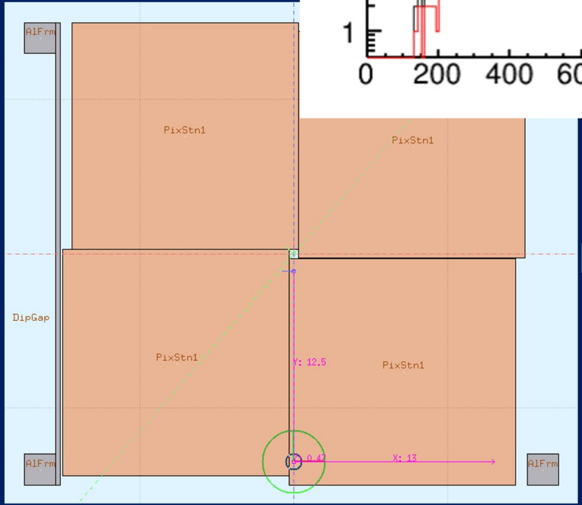
Operation conditions for vertex spectrometer

- Based on **FLUKA simulations** implementing a detailed experiment geometry
- 40 A GeV Pb beam on 5 Pb targets, 10^6 Pb/s



Upstream MAPS plane
(7.1 cm from last target)





Fluences up to 10^7/s close to the beam axis

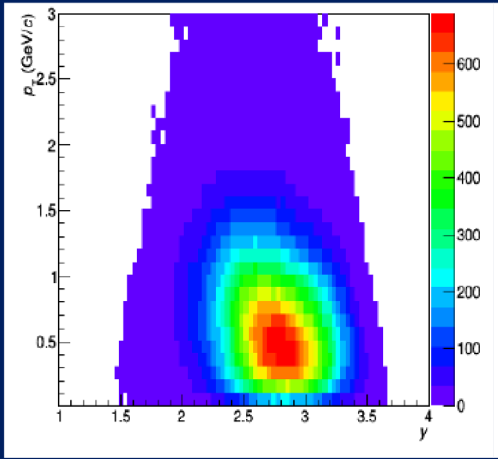
Significant contribution from δ-ray production (upward bent by dipole magnet)

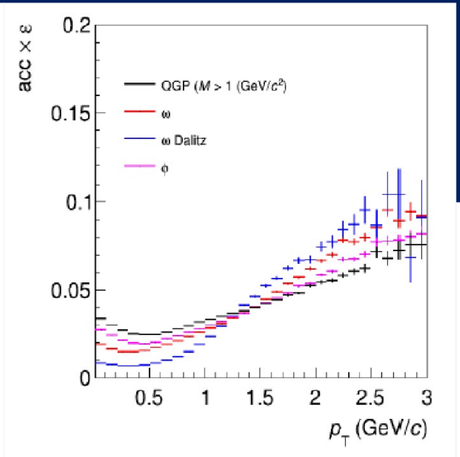
Most "exposed" sensors get a 10-15 MHz rate: 20-30 MB/s data throughput

(Di)muon detection performance

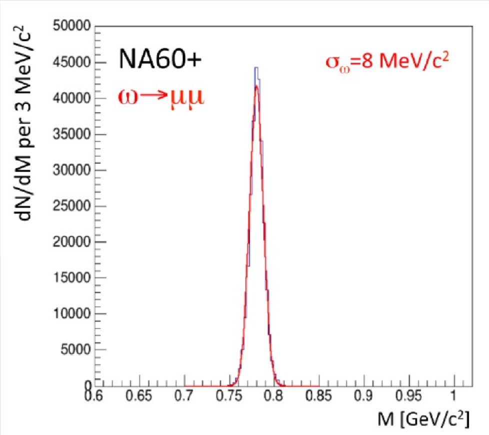
- Detector performance studies:
  - based on a **simulation framework** with a semi-analytical tracking algorithm (Kalman filter)
  - **FLUKA** for background studies

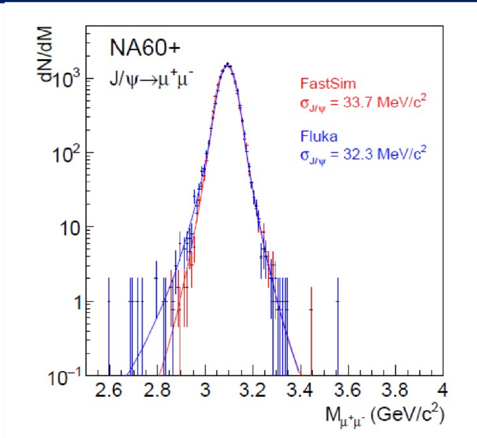
QGP (m>1 GeV/c^2)





- Full phase-space acceptance at dimuon low and intermediate masses → >1%
- Good coverage down to midrapidity AND zero p_T, realized at all energies by displacing the muon spectrometer

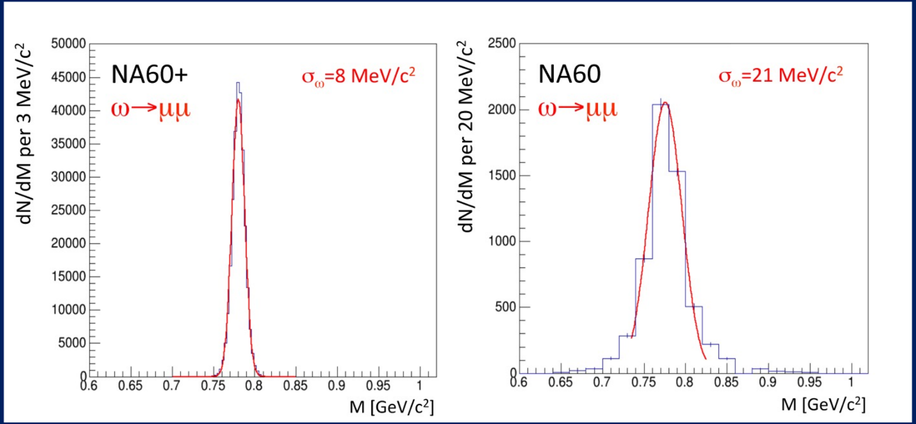




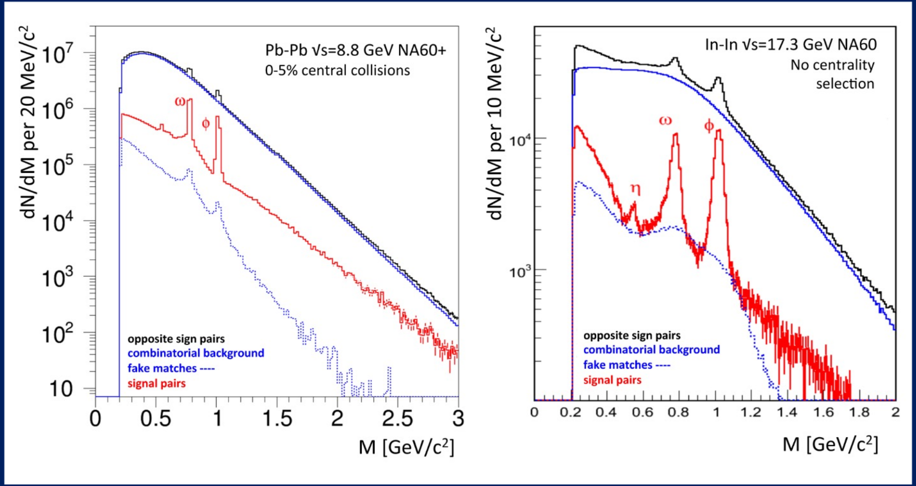
- The mass resolution for resonances varies from < 10 MeV (ω) to ~30 MeV (J/ψ):
  - Factor >2 improvement with respect to NA60

Dimuon detection performance: NA60 vs NA60+

- Detector performance studies:
  - Simulation framework tested simulating NA60 ➞ results in according to what was obtained by NA60



- The mass resolution for resonances varies from < 10 MeV/c^2 (ω) to ~30 MeV/c^2 (J/ψ):
  - Factor >2 improvement with respect to NA60 (21 MeV/c^2)



- Dimuon spectrum comparison ➞ similar signal-to-background ratio but:
  - Higher statistics
  - Better resolution
  - Centrality selection (0-5%)

D-mesons performances studies

Fast simulation:

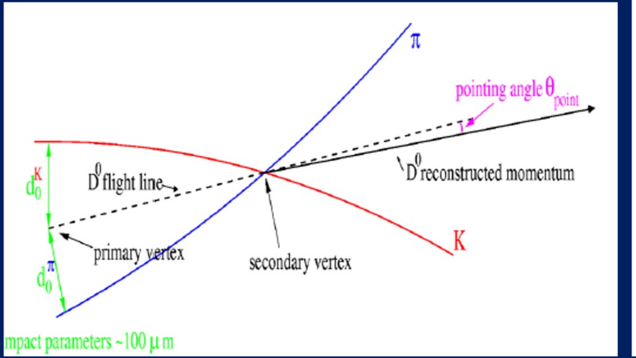
D-meson: signal simulated with p_T and y distributions from POWHEG-BOX + PYTHIA
Combinatorial background: π, K, p with multiplicity, p_T and y shapes from NA49

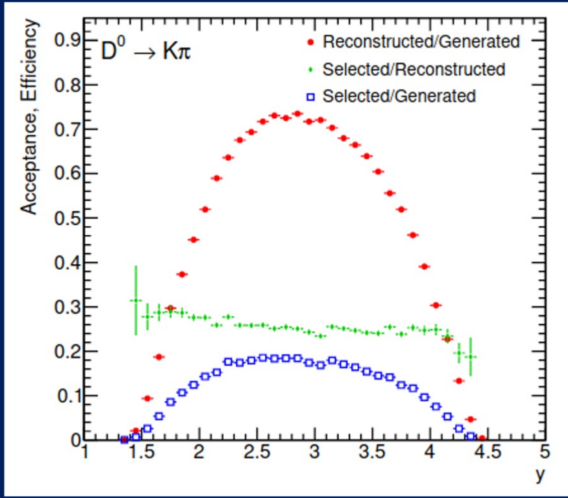
Particle transport: carried out in the VT, with parametrized simulation of its resolution
Track reconstruction: Kalman filter

D-meson vertex reconstructed from decay tracks
Geometrical selections based on decay vertex topology

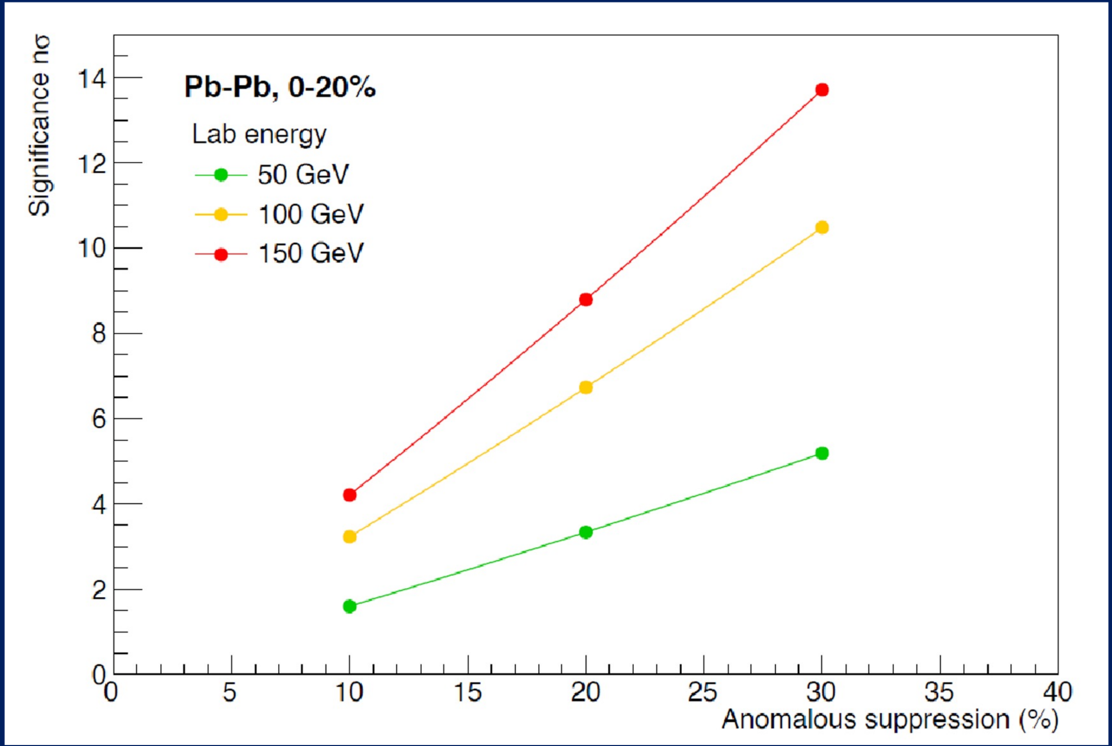
D^0 in central PbPb:

- initial S/B ~10^{-7}
- after selections S/B ~0.5





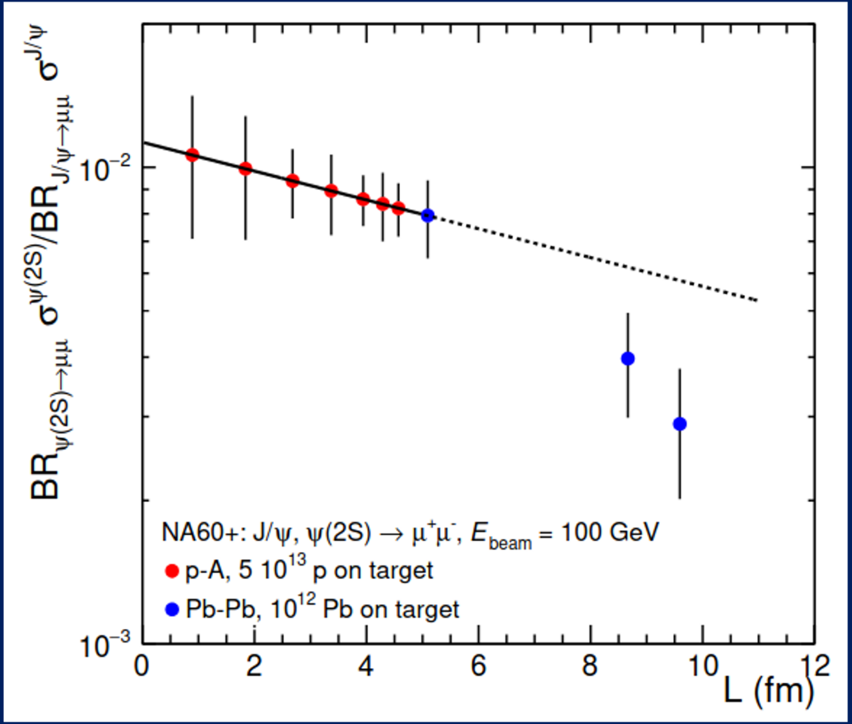
Charmonium R_{AA}



- 10% anomalous suppression signal detectable at 3σ for E_{lab}>100 AGeV
- 20% anomalous suppression signal detectable at 3σ for E_{lab}>50 GeV

ψ(2S) in pA+AA

Good charmonium resolution (30 MeV for J/ψ) will help ψ(2S) measurements:



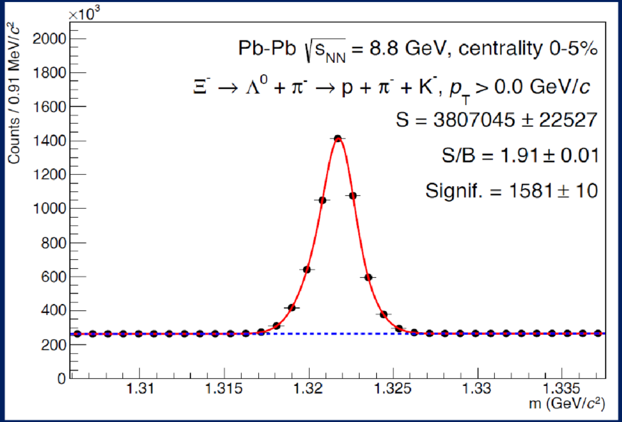
Assume

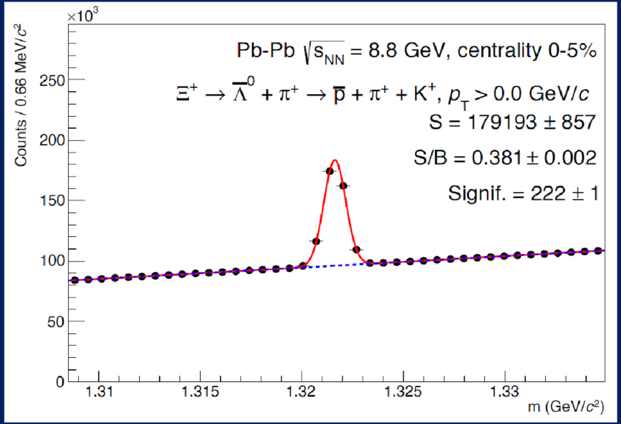
- stronger suppression for ψ(2S) than J/ψ

ψ(2S)/ψ measurement feasible down to E_{lab} ~ 100 GeV

Lower E_{lab} would require larger beam intensities/longer running times

Hyperons and strangeness





- Hyperon decays simulated with EVtGen, decay products propagated in the VT using the fast simulation of NA60+
- Background from hadron production of **NA49 results**

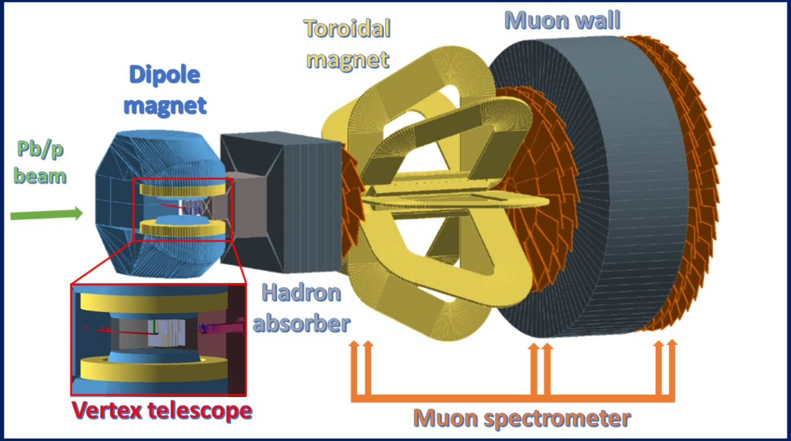
- Channels studied:

$\Lambda^0 \rightarrow p + \pi^-$ $\Xi^- \rightarrow \Lambda^0 + \pi^-$ $\Omega^- \rightarrow \Lambda^0 + K^-$

and charge conjugated

- **Topological selections** applied
- **BDT employed to enhance the significance of the signal**
- Among the variables:
  - Product of the impact parameter of decay tracks,
  - Distance of closest approach between the decay tracks
  - Decay length and the cosine of the pointing angle

NA60 vs NA60+



Some important improvements:

Physics program extended to lower energy:

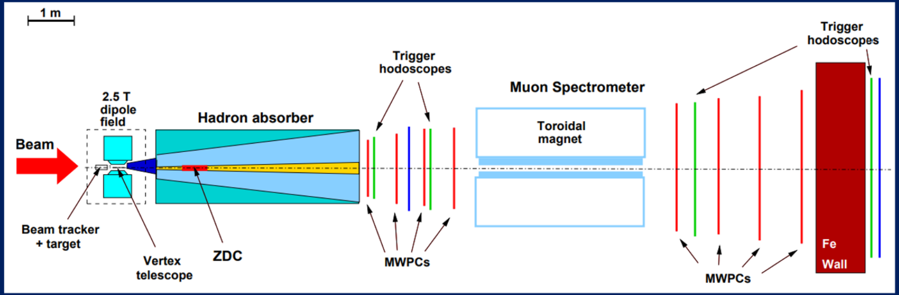
- fundamental to explore rare probes in high-μ_B region

Larger angular acceptance

- cope with lab rapidity shift when varying energy down to low SPS energy

Access new observables (open charm etc.)

- NA60: (di)muon trigger ~ 5 kHz
- NA60+: MB trigger (>100 kHz)



State-of-the art detectors

- Pixel size: from 50x425 μm^2(NA60) to 30x30 μm^2(NA60+), thinner sensors (from 2% to 0.1% X_0)
- improved resolution and signal over background: from 21 to 8 MeV at the ω mass from 70 to 30 MeV at the J/ψ mass

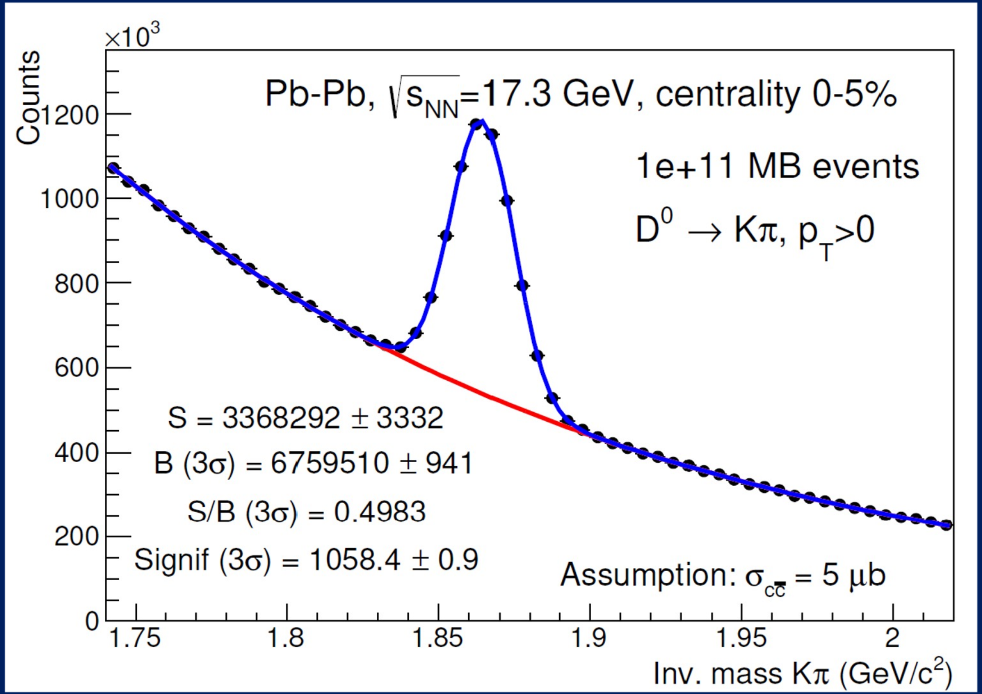
NA61 vs NA60+

NA61

Year	Beam	#days	#events	$\#(D^0 + \overline{D^0})$	$\#(D^+ + D^-)$
2022	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2023	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2024	Pb at 40*A* GeV/*c*	42	250M	3.6k	2.1k

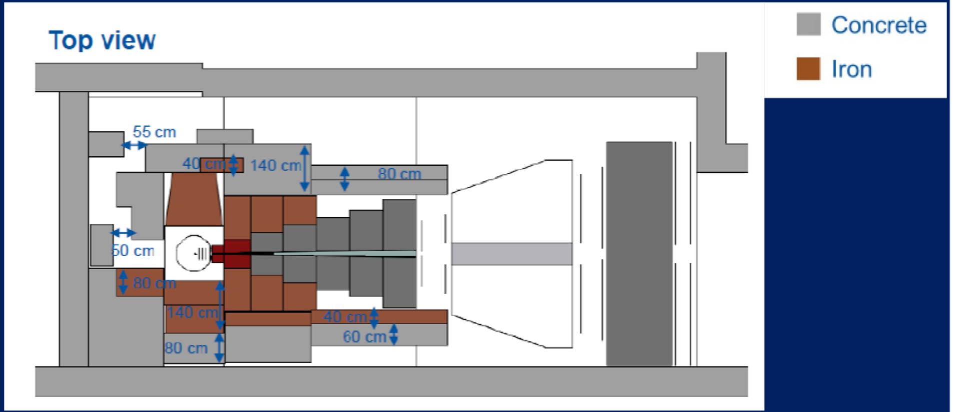
N.B.: different assumptions for open charm cross section

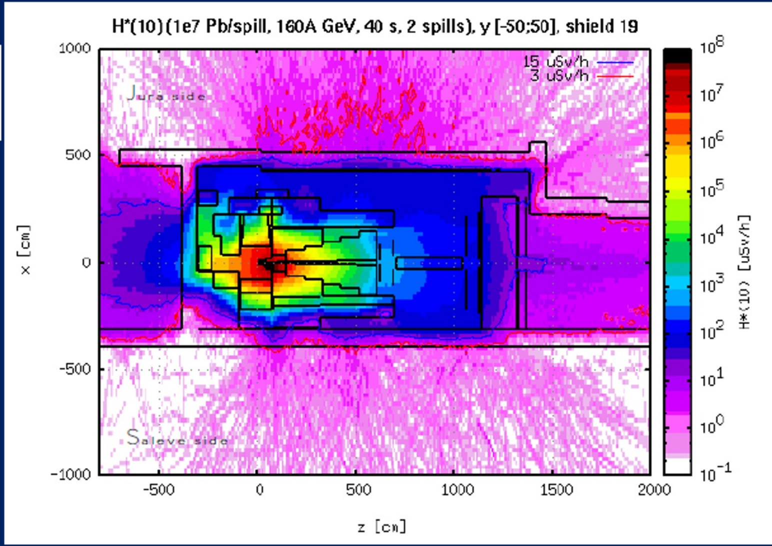
NA60+



Integration, beam and radioprotection studies

- Studies based on FLUKA geometry of the NA60+ set-up





- Installation on a surface zone implies strict requirements on radiation safety
- Dose has to be:
  - <3 µSv/h in permanent workplaces external to the experimental hall
  - <15 µSv/h in low occupancy region ➞ A thick shielding is necessary!

5. Conclusions: Feasibility Evaluation and Cost Estimation

The potential integration of the NA60+ experiment in user zone PPE138 of EHN1 has been examined concerning beam physics requirements (Chapter 2), the infrastructure integration (Chapter 3) and radiation protection (Chapter 4). **The experiment is deemed to be feasible** with regard to these aspects. The aspects of general infrastructure, detector design, data acquisition and analysis as well as the physics reach have not been evaluated.